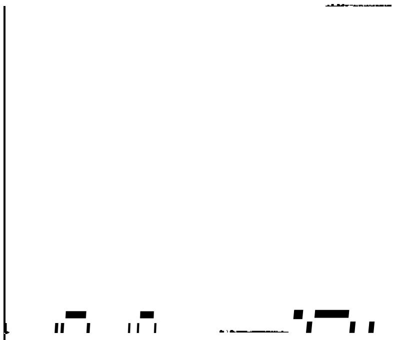

Fig. 1 Considerations for lunar base atlas.

Lunar Base

Speculation with regard to a permanent lunar base has been with us since Robert Goddard was working on the first liquid-fuelled rockets in the 1920's. With the infusion of data from the Apollo Moon flights, a onoa speculative area of space exploration has become an exciting possibility. A Moon base is not only a very real possibility, but is probably a critical element in the continuation of our piloted space programme. This article, originally drafted by World Space Foundation volunteers in conjunction with various academic end research groups, examines some of the strategies involved in selecting an appropriate site for such a lunar base. Site selection involves a number of complex variables, including raw materials for possible rocket propellant generation, hot and cold cycles, view of the sky (for astronomical considerations, among others), geological makeup of the region, and more. This article summarizes the key base siting considerations and suggests some alternatives. Availability of specific resources, including energy and certain minerals, is critical to success,

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Introduction

Of nineteen lunar surface sites explored to date, a diversity of features and characteristics have been examined. If the first lunar "resource" is Information, then the utility of a locale for the In-situ and observational sciences will rank high, Early site selection will be governed by safety, economy, and Immediate utility of the resources already known. Later site selections will depend on new knowledge of all types of resources (Fig. 1).

Present discussion of base sites is driven most strongly by the scientific community with consideration to engineering feasibility and eventual resource utilization. lunar geology, lunar geophysics and other disciplines concerning the Moon and its environs (selenology) dominate one branch of scientific utilization, while use of the Moon as a platform for astronomy, space physics, Earth and solar observations dominates the other branch. Overlying any discussion of she selection for those uses are the suitability of local terrain, viewing of the Sun, Earth and heavens, availability of energy and heat rejection paths, and local material resources.

Fig. 2 Sinuous Hadley Rille was the landing site for Apollo 15, located near the bottom-centre edge of this photograph. North is 10 the right, the Apennines lay to the East, just off the bottom edge Although there may bo more optimal lunar base sites, Hadlay Rille would be a reasonable choice

One of the earliest discussions of lunar base location was put forth in 1920 by Robert H. Goddard, a pioneer In American rocketry. He noted, "The best location on the Moon would be at the north or south pole with the [propellant] liquefier in a crater, from which the water of crystallization may not have evaporated, and with tho [solar] power plant on a summit constantly exposed to the Sun, Adequate protection should, of course, be made against meteors, by covering the essential parts of the apparatus with rock," (see p. 405, upper picture). Many would still credit him with a valid conclusion, even though geologists will offer different explanations If volatiles are found at the poles. Recent ground-based radar indications of the possibility of ice near Mercury's poles weakens some arguments against the possibility of lunar polar ice by suggesting that solar wind erosion may be less Important than proposed in limiting ice buildup.

Early locales with diverse materials are likely to outrank locales with the highest concentration of a single desired substance. The exception may be any site with a concentration of hydrogen or carbon in some form, such as Ices or subsurface gas reservoirs. Scarcity of these types of reducing agents has come to be the dominant limitation In most discussions of lunar resource utilization.

Geologists wanl 10 sample and record a diversity of terrain representing the major geologic phases of the Moon's formation and evolution. Mare and highland sampling at many sites Is considered essential, with age diversity Important.

Energy Is another resource, certainly for surface operations, and perhaps even for export, If nuclear powor Is unavailable at the required levels, energy storage equipment for the 14-day night Is Important, High crater rims and peaks near both poles may offer near-constant solar Illumination, and modest towers at these locations certainly will, but a thorough lighting survey has yet to be conducted to pin down the best locations.

Any location on the Moon would do for a partial gravity test facility for life

Portions of work reported here were performed at the Jet Propulsion Laboratory, California Institute of Technology, supported by the National Aeronautics and Space Administration. The authors gratefully acknowledge the prior work of many others referenced in the original publication, adapted here with permission of the World Space Foundation

Siting

sciences investigations. For photosensitive organisms, polar locations could offer piped-in sunlight on any day-night cycle researcher might choose,

Flight mechanics into and out of a base site can be an Important consideration. Equatorial and polar sites are favoured for their near-constant accessibility.

Slopes and terrain features can bo resources themselves. Slopes offer favoured illumination and shadowing, while craters offer natural depressions for astronomical Instruments, barriers to lander exhaust-driven debris, reactor shields and other uses. Elevation differences also figure Into some energy storage schemes.

Surface mobility will Influence sl1o selection by dictating the range d accessibility from a core base site. Subsidiary sites can serve a variety 01 specialized purposes, such as mining where different ores are accessible, Sensitive astronomical instruments will nood to be away from frequent surface activities. After accounting for the diffraction of the signals of these activities, we find that if a main base is located near the limb as viewed from Earth (i.e., 90 degrees longitude), a subsidiary site at about 101 degrees east or west longitude affords sufficient radio Isolation from Earth at the limits of the Moon's east-west libration (or "wobble").

If we had to choose a site today and be certain of a workable, if not at all optimal locale, the Apollo 15 landing site at Hadley Rille (fig. 2) would be a reasonable choice. But we can afready see superior sites, though we do not know precisely where it is safe to put the base's first landers down. Virtually all investigators agree on the wisdom of a lunar polar orbiter with suitable composition-measuring instruments plus Imaging, Surface rovers may be advisable at "finalist" sites, while teleoperated (remotely controlled) rovers will surely play an important role in exploration from any base site, Early missions could even be used to build a cache of some useful product, such as oxygen, for use by later human explorers,

As important as further lunar reconnaissance is, terrestrial development and testing of alternative resource extraction processes Is essential. Operation of one or more lunar baso analogs (as in ground-based simulations) would offer invaluable experience at a fraction of the cost of making mistakes on the Moon. Determination of the most workable and economical resource extraction processes will influence any resource-driven site selection.

Fig 3 Lunar outpost site near Mare Smythii

metho r

Base Selection Criteria

The search for potential lunar base sites is a complex undertaking. There are widely dispersed lunar sites of Interest for known and potential resources, selenology (the science ot the Moon and its environs), and observatories. Important characteristics Include certain geological and topographic features, local mineral and rock composition, solar illumination, view of Earth and tho celestial sphere, and soil engineering properties (including usability as a construction material, etc.), Space vehicle arrival and departure trajectories favor equatorial and polar sites. Over time, base sites will be developed serving different purposes. information may be tho initial lunar "resource," in the form of observational and on-site research. Resource-driven sites may see the fastest growth during early decades of lunar development, but selection of initial sites is likely to be driven *by* suitability for a combination of activities.

Only equatorial locations offer nearly all-sky views for astronomy, while most of tho far side offers radio isolation. Such Isolation could offer radio astronomers a view of the universe unfettered by television broadcasts and a host of other terrestrial Interference, A base in Mare Smythii (Fig.3) with subsidiary outposts would be favorable for a variety of purposes, and would proserve a broad resource flexibility. Discovery of accessible volatiles (substances which are easily vaporized, *such* as hydrogen, water and carbon dioxide, which often turn out to be useful for sustaining life and making rocket propellants), in the form of polar permafrost, subsurface gas reservoirs, or comet impact remnants, would dramatically increase the attractiveness of such a she from a logistical support arrd selenological point of view. For example, a ready source of water ice would alfow the manufacture of hydrogen and oxygen for the trip home or to of her destinations (It should be noted that no reliable evidence of such volatiles exists). With the availability of near-constant sunlight for power generation and permanently shadowed areas at cryogenic temperatures, polar sites require substantially loss Earth-launched mass and lower equipment complexity for an Initial base. Polar sites are, however, scientifically less interesting with their limited view of the sky and absence of important types of terrain common at lower latitudes.

Reliable evidence exists for areas of certain mineral concentrations, such as ilmenite, which could form a feedstock for some proposed resource extraction schemes, In addition to being a source for oxygen and iron, ilmenite (composed of iron, titanium, and oxygen) harbors higher concentrations of solar wind-implanted hydrogen, carbon, nitrogen and helium. These elements were apparently exhausted from the Moon during its formation and evolution, but minor concentrations have collected out of the tenuous plasma discharged from tho Sun and driven across the Solar System as the Solar wind. New data from a lunar polar orbiter are essential for the most Informed site selection. Data from the first Galileo flyby have already revealed previously unknown features and will aid surface mineralogical characterization.

The Present Understanding of the Moon

The last unmapped region of tho Moon, near the south pole, was photographed during the December 8, 1990 Galileo flyby, but there Is a great deal more that would be helpful to know In selecting base sites, From Ranger through Apollo the trend has been to open up mission constraints to afford better scientific opportunities. Apollo 11 was sent to a flat mare region for safety. In contrast, the Apollo 17 site was selected for Its geological diversity within a small area (Fig.4).

I-he last three Apollos carried a set of orbital Instruments designed to map the surface et fine resolution and infer Its composition, but near-equatorial orbits limited their coverage to less than 20% of the Moon. Crude geologic maps of the entire surface havo been constructed from the best available data of all types.

Information needed for selecting the best base sites depends on the objectives of these bases. However, some kinds of data are required for nearly any base. local topography is an obvious need, and most investigators agree that, except for the immediate vicinity of the Apollo sites, present information is inadequate. Even without elevation data, positions of features are typically uncertain by 1-3 km on the near side, by 3-6 km poleward of 65 degrees latitude, and by '3-15 km on the far side (It is Important to remember, though, that terrestrial explorers seldom knew their locations a fraction as accurately).

An orbiting laser altimeter and a metric camera system offer the preferred means for improving lunar topographic maps. Knowing topographic obstacles is essential for safe approach from and departure to orbit, as well as for designing solar power and thermal radiation Installations for a specific site. Spatial resolution of 1 meter or better is preferred to certify landing sites.

1 he next most important new information probably concerns the subsurface mechanical properlies, to a depth of at least a meter, that affect digging, foundation-building and other preparations al any specific site. Where mining is contemplated, such information is important to a greater depth. Though the lunar surface has been somewhat homogenized by Impacts, It does vary in state of compaction, grain size distribution, sizo of embedded rocks and other mechanical properties.

While compositional properties may be iess important than local topography and soil mechanics during tho earnest lunar operations, composition will dominate once resource development begins. Compositional information is therefore highly desirable even before choosing the first base site,

Multispectral remote sensing from orbit provides needed regional data, after which surface traverses are best tor detailing the most promising locales, Long range rovers teleoperatod from Earth carrying imaging, geochemical and geophysical instruments, would bo suitable for both scientific and resource she reconnaissance. Use of these rovers could continue during base build-up.

Depending on a short list of candidate sites, different kinds of local information may be useful for selecting a final site. For a polar site, an orbiter with altimetry and metric Imaging could perform a survey of varying surface lighting conditions for siting solar power generators, radiators and Instruments. In the event an orbiter detects indications of volatiles near one of the poles, surface exploration may be required for precise location. In a similar fashion, it could prove useful to explore volcanic ar-

Fig. 4 Arrow Indicates 1110 Apollo 17 landing site near a variety of geologically interesting formations.

Surface *Transportation*

***Lunar Outpost* is** the title of **a publication that depicts concepts developed during the Lunar Base Systems Study undertaken by tho Advanced Programs Oftice, In the Engineering Directorate of tho Johnson Spaco** CentOr, In 1988-88, it **was recognised** at the tlmo **that** tho spacecraft concepts presented may not be the ones that **will** eventually **fly** and that some of tho **elements** described may not even be **built. Its** purpose **was** not to **present** a preferrod path or "road map" to the Moon, but to **enlighten** tho reador on tho needs of **lunar exploration** and development, and to **challenge** the reader **to** formulate new **ideas** and concepts, We **present** here tho **section** on **'Surface Transportation'.**

Lunar surface transportation is designed to move people and equipment to accomplish local objectives and perform long distance missions including the mapping and surveying of future mining and resource sites. Other construction tasks, such as excavation or large equipment assembly, will be accomplished by specially designed construction equipment.

The operating conditions for surface vehicles will be very different from terrestrial travel conditions. 1 he Moon has one-sixth tho gravity of Earth, practically zero atmosphere, extreme temperature swings (10? K to 384 K, or -250°F to +257°F, at the Apollo 17 site), and almost no magnetic field to provide protection from radiation. The vehicles required for lunar operation must not only survive this environment but do so over many years.

When humans return to the Moon, the surface vehicles will be designed with the help of pasl experience - Apollo missions 11, 1 ? and 14 through 17, and the unmanned Soviet Lunokhod 1.

Two types of transportation vehicle will be required during the buildup phase of the lunar outpost: an unpressurised rover for local transportation, and a pressurised vehicle for long-range travel

The local rover, LOTRAN (local transportation vehicle, unpressurised), is designed for a range of 100 km with a maximum speed of 15 km/h Its passive suspension In the form of metal-elastic wheels simplifies the design by reducing the number of moving parts and opportunities for failure. The vehicle is fully articulated at two joints, allowing for obstacle avoidance and/or negotiation. It can carry two crewmembers plus 850 kg of

This lunar landscape depicts the arrival of a modular chamber from Earth that could be used to form living and work quarters for personnel. The unit will be moved to the site in the background and buried for protection from meteor impacts. *NASA artwork by Pat Rawlings*

eas, such as the region around Aristarchus, for possible vents and associated mineralization, lava tubes which could make natural base shelters and other physical and compositional features (Fig. 5).

Material Resources

First consideration of material resources is *given* to a site's ability to

MOSAP and LOT RAN vehicles on a scouting mission. *JSC/NASA*

payload or two additional crewmembers, depending on the task requirements. The second joint can be disconnected for trips not requiring the trailer section,

The pressurised vehicle system, MOSAP (mobile surface application traverse vehicle), has a maximum range of 3000 km with a nominal speed of 10 km/h, It also has a passive suspension in the form of cone wheels, The complete system is a four-piece modular design to allow flexibility in mission planning. Each of the four units can be individually operated or connected In the train configuration shown below and controlled by the first unit, the primary control research vehicle (PCRV). The units following the PCRV are the habitation trailer unit, the auxiliary power cart, and the experiment and sample trailer, Most tasks, such as crew transfer and medium distance survey or sample collection, will require only the PCRV.

Extremely long traverses will be accomplished by using a landing craft with crew module flying round trip from lunar orbit. Basing the landing craft at the outpost and "hopping" from site to site would not be as energy efficient.

Reference

John Alred *et al*, *Lunar Outpost*, Johnson Space Center **1989.**

Fig 5 The area around the young crater Ark ... thus is of volcanic origin

support local operations. At least meter-deep (and preferably deeper) regolith (loose soil) is desirable for burying initial habitation structures to suitable depth for long term cosmic ray and solar flare shielding. Two meters of 100so material protecting inhabited structures from all directions, achieved by a combination of trenching and burying, is considered adequate. Mechanical properties should offer easy excavation. Ilmenite-rich mare (lunar "sea", or lowland) soil provides slightly superior radiation protection for a given thickness than lower density highland material, but this Is not likely to be decisive advantage in base construction.

Second consideration is given to reducing the need for costly importation of terrestrial material for functions easily replaced by lunar material. Perhaps the simplest processed lunar material is cast basalt (a family o! Igneous rocks common to the Earth and Moon, formed when certain types of lava cool on the surface. An example of basalts are the majority of the Hawaiian Islands and lunar maria). Results from Earth-based testing indicate that basalts appear to be of suitable composition to be melted, poured Into forms, and cooled into bricks and more complex structural forms. It can also be spun Into Insulating rock wool, as has been done In some terrestrial industries for decades. Melting and sintering (heating and forming without melting) temperatures are about 200 degrees celsius less for lowland mare basalts than for typical highland materials, arrd therefore require less process heal, Materials for production ot some metals, solar cells, cement (based on CaO, calcium oxide), concrete, etc. may be more easily extracted from highlands although concentrates from mare materials will be adequate. Some highland materials produce a higher-strength, more transparent glass. For simple building materials, a mare site is superior but highland materials will work.

Volatiles In lunar samples have been shown to originate from solar wind implantation. Concentrations of hydrogen, carbon and nitrogen, the most valuable for life support and propellant, are available from lunar soils and regolith breccias (a rock composed of chunks of smaller, older rocks which have been fused together in a geologic process). Because these elements implant over time on the surface of mineral grains, their mass concentrations are highest on smaller grains in older soils. Concentrations are much lower In solid Igneous (volcanic) rocks. Retention on ilmenite grains Is preferential to other common minerals. It is not clear that the bulk availability of solar wind-implanted hydrogen, carbon or nitrogen is sufficient for practical production quantities of propellant, Other possible sources of volatile compounds include cometary impacts. Water, carbon dioxide, methane, hydrogen sulfide, ammonia or other volatiles are unlikely to last long near the impact points, but could collect In polar cold traps.

Simple heating of lunar soils to 700 degrees C will liberate most of the volatiles, with heating above 1050 degrees C required to obtain most of the rest. Splar-driven processes could yield sufficient gases to make up for habitat leakage and other losses. Young crater rims and ejecta blankets are probably deficient in Implanted volatiles; other areas with sufficient regolith depth (probably most of the Moon) are likely to be satisfactory, though there may be a preference for Ilmenite-enriched regions.

Specialized ore bodies could take several forms. First, "ore" should be defined as a natural concentration of a useful substance 10 a level and in a form which makes its extraction economical. Most mineral concentrations remain to be discovered. Even on Earth, ore bodies are seldom discovered and never confirmed without on-site sampling. At this point we can only suggest a few kinds of lunar materials which might prove important to base location. A preliminary list could read, in descending order of Importance: mare basalt regolith, ilmenite, iron, pyroclastic glasses with semi-volatiles, high aluminum content highland material, and KREEP (Potassium Rare-Earth Elements, Phosphorus),

Ilmenite has been discussed as a feedstock for oxygen production by chemical reduction, for its higher solar wind volatiles content, and for the potential to beneficiate (a preparation for processing where the useful content of the ilmenite Is enriched) It from soil using relatively simple electrostatic techniques, However, no one has yet demonstrated that naturally occurring lunar ilmenite can be adequately separated from accompanying substances to form a suitable cost-effective feedstock. Therefore, ilmenite availability as a major siting criterion could be a trap. Early use of ilmenite is less often described In terms of a source of iron or titanium. Ilmenite is especially abundant (up to 20% by volume) in some Apollo 11 and Apollo t7 mare basalts. Ilmenite is most often associated with high- titanium basalts in maria. Metallic iron and rrickel-iron grains make up a small fraction of soil, apparently tho product of meteoroid impacts, lava crystallization and a chemically reducing environment. While not considered an important early base siting criterion, availability of reduced metals such as Iron could become important later. Older terrains, with deeper regolith, presumably have more metallics, i.e., iron and nickel, which may be easily beneficiated magnetically,

For oxygen extraction, magma electrolysis (passing an electric current through molten rock), high temperature pyrolysis (alteration through heat) and fluoride processing are somewhat site-independent, though process energies may vary. Ilmenite reduction and pyroclastic glass processing require site-variable feed. stocks (pyroclastic glasses are typically tiny broken beads, formed in explosive meteoroid impacts or volcanic events. They form when bits of molten rock cool too rapidly to form crystalline grains).

A conclusion of the April, 1990 Johnson Space Center lunar base workshop participants bears repeating: "... .We conclude that from the point of view of resource utilization, a viable strategy would bo to select a high titanium mare site, perhaps on or near a pyroclastic area, and near a highland area so that calcium-rich feedstock would also be available,. ."

Reference

John S Lewis, Mildred S. Matthews and Mary L, Guerrieri, Editors, *Resources of Near-Earth Space*, University of Arizona Press, Tucson & London, 1993.

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Lunar Base

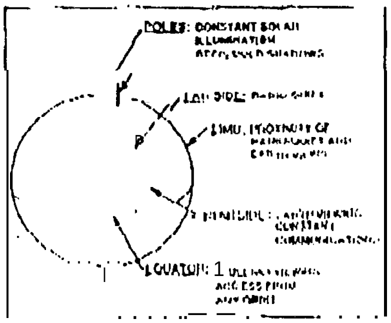

Fig. 1 Considerations for lunar base sites.

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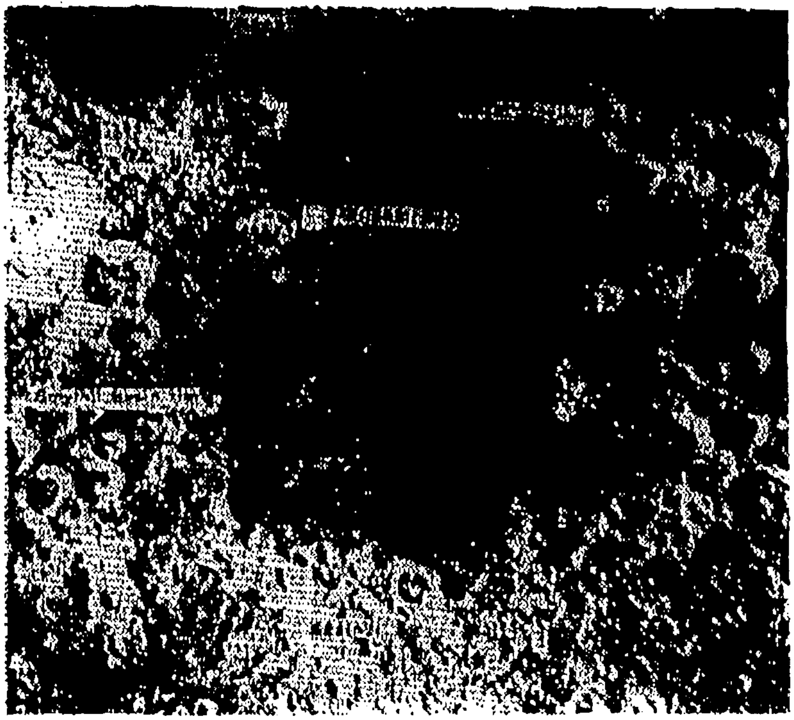

Fig. 3 Lunar outpost site in Mare Smythii.

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Fig. 4 Arrow indicates the Apollo 17 landing site near a variety of geologically interesting formations.

size distribution, size of embedded rocks and other mechanical properties.

While compositional properties may be less important than local topography and soil mechanics during the earliest lunar operations, composition will dominate once resource development begins. Compositional information is therefore highly desirable even before choosing the first base site.

Multispectral remote sensing from orbit provides needed regional data, after which surface traverses are best for detailing the most promising locales. Long range rovers teleoperated from Earth carrying imaging, geochemical and geophysical instruments, would be suitable for both site studies and resource site reconnaissance. Use of these rovers could continue during base build-up.

Depending on a short list of candidate sites, different kinds of local information may be useful for selecting a final site. For a polar site, an orbiter with altimetry and metric imaging could perform a survey of varying surface lighting conditions for siting solar power generators, radiators and instruments. In the event an orbiter detects indications of volatiles near one of the poles, surface exploration may be required for precise location. In a similar fashion, it could prove useful to explore volcanic ar-

Surface Transportation

Lunar Outpost is the title of a publication that depicts concepts developed during the Lunar Base Systems Study undertaken by the Advanced Programs Office, in the Engineering Directorate of the Johnson Space Center, in 1988-89. It was recognised at the time that the spacecraft concepts presented may not be the ones that will eventually fly and that some of the elements described may not even be built. Its purpose was not to present a preferred path or "road map" to the Moon, but to enlighten the reader on the needs of lunar exploration and development, and to challenge the reader to formulate new ideas and concepts. We present here the section on 'Surface Transportation'.

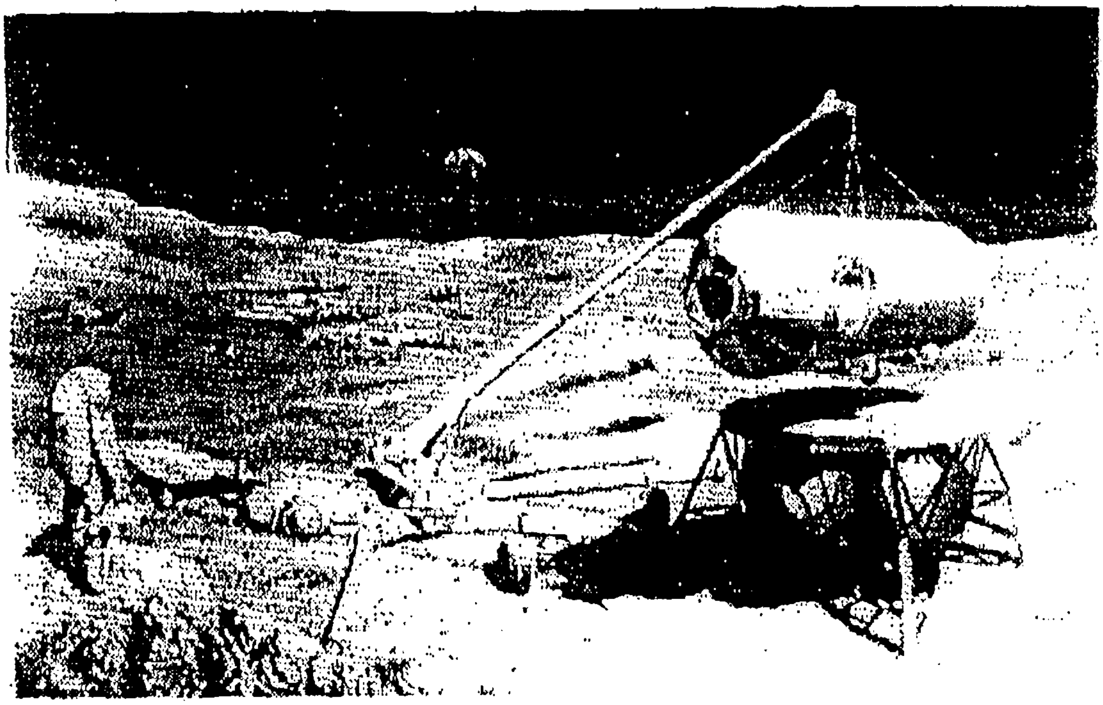
Lunar surface transportation is designed to move people and equipment to accomplish local objectives and perform long distance missions including the mapping and surveying of future mining and resource sites. Other construction tasks, such as excavation or large equipment assembly, will be accomplished by specially designed construction equipment.

The operating conditions for surface vehicles will be very different from terrestrial travel conditions. The Moon has one-sixth the gravity of Earth, practically zero atmosphere, extreme temperature swings (102 K to 384 K, or -250°F to +257°F, at the Apollo 17 site), and almost no magnetic field to provide protection from radiation. The vehicles required for lunar operation must not only survive this environment but do so over many years.

When humans return to the Moon, the surface vehicles will be designed with the help of past experience - Apollo missions 11, 12 and 14 through 17 and the unmanned Soviet Lunokhod.

Two types of transportation vehicle will be required during the buildup phase of the lunar outpost: an unpressurised rover for local transportation, and a pressurised vehicle for long-range travel.

The local rover, LOTRAN (local transportation vehicle, unpressurised), is designed for a range of 100 km with a maximum speed of 15 km/h. Its passive suspension in the form of metal elastic wheels simplifies the design by reducing the number of moving parts and opportunities for failure. The vehicle is fully articulated at two joints, allowing for obstacle avoidance and/or negotiation. It can carry two crewmembers plus 850 kg of



This lunar landscape depicts the arrival of a modular chamber from Earth that could be used to form [illegible] The unit will be moved to the site in the background and buried for protection from meteor impacts. [illegible]

eas, such as the region around Aristarchus, for possible vents and associated mineralization, lava tubes which could make natural base shelters and other physical and compositional features (Fig. 5).

Material Resources

First consideration of material resources is given to a site's ability to

MOSAP and LOTRAN vehicles on a scouting mission. *JSC/NASA*

payload or two additional crewmembers, depending on the task requirements. The second joint can be disconnected for trips not requiring the trailer section.

The pressurised vehicle system, MOSAP (mobile surface application traverse vehicle), has a maximum range of 3000 km with a nominal speed of 10 km/h. It also has a passive suspension in the form of cone wheels. The complete system is a four-piece modular design to allow flexibility in mission planning. Each of the four units can be individually operated or connected in the train configuration shown below and controlled by the first unit, the primary control research vehicle (PCRV). The units following the PCRV are the habitation trailer unit, the auxiliary power cart, and the experiment and sample trailer. Most tasks, such as crew trans fer and medium distance survey or sample collection, will require only the PCRV.

Extremely long traverses will be accomplished by using a landing craft with crew module flying round trip from lunar orbit. Basing the landing craft at the outpost and "hopping" from site to site would not be as energy efficient.

Reference

John Alred et al, Lunar Outpost, Johnson Space Center, 1988.

→ other reference

Fig. 6 The area around the young crater Aristarchus is of volcanic [illegible]

support local operations. At least meter-deep (and preferably deeper) regolith (loose soil) is desirable for burying initial habitation structures to suitable depth for long term cosmic ray and solar flare shielding. Two meters of loose material protecting inhabited structures from all directions, achieved by a combination of trenching and burying, is considered adequate. Mechanical properties should offer easy excavation. Ilmenite-rich mare (lunar "sea", or lowland) soil provides slightly superior radiation protection for a given thickness than lower density highland material, but this is not likely to be decisive advantage in berm construction.

Second consideration is given to reducing the need for costly importation of terrestrial material for functions easily replaced by lunar material. Perhaps the simplest processed lunar material is cast basalt (a family of igneous rocks common to the Earth and Moon, formed when certain types of lava cool on the surface. An example of basalts are the majority of the Hawaiian Islands and lunar maria). Results from Earth-based testing indicate that basalts appear in be of suitable composition to be melted, poured into forms, and cooled into bricks and more complex structural forms. It can also be spun into insulating rock wool, as has been done in some terrestrial industries for decades. Melting and sintering (heating and forming without melting) temperatures are about 200 degrees celsius less for lowland mare basalts than for typical highland materials, and therefore require less process heat. Materials for production of some metals, solar cells, cement (based on CaO, calcium oxide), concrete, etc. may be more easily extracted from highlands although concentrates from mare materials will be adequate. Some highland materials produce a higher-strength, more transparent glass. For simple building materials, a mare site is superior but highland materials will work.

Volatiles in lunar samples have been shown to originate from solar wind implantation. Concentrations of hydrogen, carbon and nitrogen, the most valuable for life support and propellant, are available from lunar soils and regolith breccias (a rock composed of chunks of smaller, older rocks which have been fused together in a geologic process). Because these elements implant over time on the surface of mineral grains, their mass concentrations are highest on smaller grains in older soils. Concentrations are much lower in solid igneous (volcanic) rocks. Retention on ilmenite grains is preferential to other common minerals. It is not clear that the bulk availability of solar wind-implanted hydrogen, carbon or nitrogen is sufficient for practical production quantities of propellant. Other possible sources of volatile compounds include cometary impacts. Water, carbon dioxide, methane, hydrogen sulfide, ammonia or other volatiles are unlikely to last long near the impact points, but could collect in polar cold traps.

Simple heating of lunar soils to 700 degrees C will liberate most of the volatiles, with heating above 1050 degrees C required to obtain most of the rest. Solar-driven processes could yield sufficient gases to make up for habitat leakage and other losses. Young crater rims and ejecta blankets are probably deficient in implanted volatiles; other areas with sufficient regolith depth (probably most of the Moon) are likely to be satisfactory, though there may be a preference for ilmenite-enriched regions.

Specialized ore bodies could take several forms. First, "ore" should be defined as a natural concentration of a useful substance to a level and in a form which makes its extraction eco-

[illegible]

Ilmenite has been discussed as a [illegible] for oxygen production [illegible], [illegible] higher [illegible] content, and [illegible] potential [illegible] [illegible] could [illegible] soil using relatively simple electrostatic techniques. However, no one has yet demonstrated that naturally occurring lunar ilmenite can be adequately separated from accompanying substances to form a suitable cost-effective feedstock. Therefore, ilmenite availability as a major siting criterion could be a trap. Early use of ilmenite is less often described in terms of a source of iron or titanium. Ilmenite is especially abundant (up to 20% by volume) in some Apollo 11 and Apollo 17 mare basalts. Ilmenite is most often associated with high titanium basalts in maria. Metallic iron and nickel iron grains make up a small fraction of soil, apparently the product of meteoroid impacts, lava crystallization and a chemically reducing environment. While not considered an important early base siting criterion, availability of reduced metals such as iron could become important later. Older terrains, with deeper regolith, presumably have more metallics, i.e., iron and nickel, which may be easily beneficiated magnetically.

For oxygen extraction, magma electrolysis (passing an electric current through molten rock), high temperature pyrolysis (filtration through heat) and fluoride processing are somewhat site-independent, though process energies may vary. Ilmenite reduction and pyroclastic glass processing require site-variable feedstocks (pyroclastic glasses are typically tiny broken beads, formed in explosive meteoroid impacts or volcanic events. They form when bits of molten rock cool too rapidly to form crystalline grains).

A conclusion of the April, 1990 Johnson Space Center lunar base workshop participants bears repeating: "...We conclude that from the point of view of resource utilization, a viable strategy would be to select a high titanium mare site, perhaps on or near a pyroclastic area, and near a highland area so that calcium-rich feedstock would also be available...".